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THESIS

NUMERICAL ANALYSIS OF
DOUBLE DELTA ANTENNAS
VOLUME I

by

Achmad Chafid

December 1988

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The Double Delta antenna is an HF communication antenna which exists in many forms throughout military communication commands. Performance characteristics for existing designs are presently unknown and are required in order to recommend an optimum design.

This thesis investigates Double Delta antennas used by the US Army (lowband and highband), the US Air Force (lowband and highband), and a commercial model. Selected models are analyzed by a computer simulation method using the Numerical Electromagnetics Code (NEC). The antenna designs are investigated to determine optimum performance characteristics over the 2 - 30 MHz range of frequencies. The parameters calculated were input impedance, VSWR, and antenna gain radiation patterns. For the performance of the antennas when sited near lossy ground, the Sommerfeld method was employed. Finally the results of the evaluation are presented and recommendations are made.

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Numerical Analysis of Double Delta Antennas Volume I

by

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ABSTRACT

The Double Delta antenna is an HF communication antenna which exists in many forms throughout military communication commands. Performance characteristics for existing designs are presently unknown and are required in order to recommend an optimum design.

This thesis investigates Double Delta antennas used by the US Army (lowband and highband), the US Air Force (lowband and highband), and a commercial model. Selected models are analyzed by a computer simulation method using the Numerical Electromagnetics Code (NEC). The antenna designs are investigated to determine optimum performance characteristics over the 2 - 30 MHz range of frequencies. The parameters calculated were input impedance, VSWR, and antenna gain radiation patterns. For the performance of the antennas when sited near lossy ground, the Sommerfeld method was employed. Finally the results of the evaluation are presented and recommendations are made.

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Finally my thanks to Lieutenant Commander USN Calvin P Langford for his guidance at the beginning of my work on this thesis.

I. INTRODUCTION

A. BACKGROUND

The double delta antenna is constructed from two crossed triangular loop antennas oriented at a certain angle to each other. In general, there are two types of loop antennas, a circular loop antenna and a polygonal loop antenna. By selecting an appropriate shape of loop antenna, broadband impedance characteristics can be expected. This antenna provides a radiation pattern with the major lobe perpendicular to the earth's surface; therefore, it could be used to determine the height and the critical frequency of the ionospheric layer directly above a station. It is also useful for short-range ionospheric HF communication. The most common double delta antenna is fed from the center of a horizontal wire (base-driven) and loaded at the top. There are many double delta antennas used for both military and commercial purposes. Throughout this thesis, the double delta antenna, along with its many characteristics, will be discussed.

B. PROBLEM ENVIRONMENT

This thesis investigates the Double Delta antenna used by the US Army (lowband and highband), the US Air Force (lowband and highband) and the ESI 32A2A, sold commercially. Performance characteristics for these models are required in order to obtain an optimum design. Therefore there is a need to study the characteristic parameters of these antennas.

1. Antenna Parameters

a. Impedance

The input impedance is described as the impedance (voltage to current ratio) presented by the antenna at its feed terminals.

The input impedance can be defined as follows :

$$Z_{in} = R_{in} + jX_{in} \tag{1}$$

where :

- Z_{in} is the antenna impedance at its terminals
- R_{in} is the antenna resistance at its terminals
- X_{in} is the antenna reactance at its terminals

The resistive part alone consists of two components :

$$R_{in} = R_r + R_L \tag{2}$$

where :

- R_r is radiation resistance of the antenna
- R_L is loss resistance of the antenna

Radiation resistance R_r represents power that leaves the antenna as radiation, while loss resistance R_L represents power dissipation due to antenna structure losses. Input reactance, X_{in}, is related to relative power storage in the near field of the antenna. The antenna input impedance is very important in order to avoid losses when power is transfered from the system to the antenna or from the antenna to the system. The maximum transfer can be achieved if the antenna impedance "matches" the impedance of the system. Matching occurs when one impedance is the conjugate of another [Ref. 1].

b. Voltage Standing Wave Ratio (VSWR).

If the system were operated with a poor match at the antenna there would be reflections set up along the transmission line. Therefore, the voltage standing wave ratio (VSWR) is much greater than one. In many applications the VSWR is not high, but an extremely low VSWR is also not a necessity. For example, a VSWR = 2 leads to 89 percent power transmission. On the other hand, if the VSWR is very high, power will travel back and forth along the transmission line, and, if the line is lossy and/or of long length, dissipative losses may be significant [Ref. 2].

VSWR can be related to impedances :

$$VSWR = \frac{1 + \sqrt{\dfrac{(R_L - R_0)^2 + X_L^2}{(R_L + R_0)^2 + X_L^2}}}{1 - \sqrt{\dfrac{(R_L - R_0)^2 + X_L^2}{(R_L + R_0)^2 + X_L^2}}} \tag{3}$$

where :

- R_L is the antenna resistance
- X_L is the antenna reactance
- $R_0 = Z_0$ of the transmission line

The percentage of reflected power can be related to VSWR using the equation :

$$P_r = \left[\frac{(VSWR-1)^2}{(VSWR+1)^2} \right] \times 100\% \tag{4}$$

where P_r is the percent reflected power.

c. *Average Power Gain*

Another useful parameter describing the performance of an antenna is gain. Measurements can provide efficiency of the antenna as well as its directional radiation capability. A common criteria applied to an antenna computer model is given by calculating the average power gain. It is obtained by integrating the radiated power density to find the total radiated power, and then comparing that with the total input power at the feed points. The comparison will show equal values for a valid solution. The average power gain is a useful criteria for checking the accuracy of computing the input impedance for any computer model of a wire antenna. The average gain should equal 1 for an antenna in free space and equal 2 for an antenna over perfectly conducting ground; otherwise the model may not be correct. Because the ideal value is not always reached in real-world applications, an acceptable tolerance is considered. For engineering purposes, an average power gain within 10 percent of ideal is acceptable [Ref. 3].

C. SCOPE AND LIMITATION

This thesis investigates the Double Delta antenna from the US Army (lowband and highband) and the USAF (lowband and highband), plus the commercially produced ESI 32A2A. The first analysis conducted is the investigation of input impedance, VSWR, and radiation patterns. References for normalizing impedances of 50, 300 and 600 ohms were used to compute the input impedance and VSWR. Radiation patterns were computed for elevation and azimuth planes. The vertical gain elevation power pattern was computed for 91 points of θ at ϕ equal 0 degrees and 91 points of θ at ϕ equal 90 degrees. The horizontal gain azimuth power pattern was computed for 91 points of ϕ at θ equal 70, 50, 30, and 10 degrees respectively.

Performance of these antennas over real ground conditions are also of interest for the following parameters :

1. Poor ground conditions :
   - Relative dielectric constant of ground $\varepsilon_r = 5$
   - Conductivity of ground $\sigma = 10^{-3}$ mhos/m
2. Fair ground (average ground) conditions :

- Relative dielectric constant of ground $\varepsilon_r = 12$
- Conductivity of ground $\sigma = 5 \times 10^{-3}$ mhos/m

3. Good ground conditions :
   - Relative dielectric constant of ground $\varepsilon_r = 30$
   - Conductivity of ground $\sigma = 10^{-2}$ mhos/m

Throughout this thesis, a special program called NEC - *Numerical Electromagnetics Code* - is used [Ref. 3]. Computations were done with a single precision version which was found to be sufficiently accurate. To accurately model wire antennas near lossy ground via NEC, the computationally intensive Sommerfeld method is required. Initial tests of the sensitivity of DD antennas to ground constants revealed the fact that very little variation in gain occurs (less than 1.5 dB) as ground conditions vary from poor to fair and from fair to good. Time and computer resource limitations justify the choice of one set of conditions - fair ground - for this investigation.

This thesis devided into two volumes, Volume I and Volume II. Volume I presents the antennas were investigated, method for investigation, and the results of investigation. Volume II contains Appendix C, the plots of input impedance, VSWR, and maximum gain versus frequency and plots of radiation patterns for each frequency for the antennas.

II. ANALYSIS OF DOUBLE DELTA ANTENNAS

A. DESCRIPTION

1. The Army Lowband Double Delta Antenna

Figure 1 shows the NEC wire model of the Army Lowband DD antenna from the Army Signal Corps publication TM 11-486-6. The antenna consists of two separate different size delta antennas, installed perpendicular to one another forming an assymmetric double delta. This antenna is designed for operation during the low-frequency portion of the nominal 11.1 year solar cycle, when the majority of the critical frequencies fall in the lower end of the HF band. The effective gain over the low-frequency end of the band is provided by increasing the antenna leg dimensions [Ref. 4]. The following parameters specify the Army Lowband Double Delta antenna :

1. Two long arms : 150 feet each
2. Two short arms : 65 feet each
3. Top height : 65 feet
4. Top loading : 600 ohms
5. Frequency : 2 to 8 MHz
6. Arm height : 3 feet

The structure is fed at the center of the arms. The model is simulated over perfectly conducting ground and fair ground using the Sommerfeld method. (This is true for all Double Deltas in this study).

2. The Army Highband Double Delta Antenna

Figure 2 shows the Army Highband Double Delta antenna from the Army Signal Corps publication TM 11-486-6. The antenna consists of two identical delta antennas, installed perpendicular to each other forming a symmetric double delta antenna. The two delta antennas are identical, except for the terminating resistances. The receiving delta antenna only requires a very low wattage resistor. The transmitting termination must be capable of dissipating one half of the average power of the transmitter output. This antenna is installed for operation during the high-frequency portion of the solar cycle [Ref. 4]. The following specify the Army Highband Double Delta antenna :

1. Four symmetric arms : 65 feet each
2. Top height : 65 feet

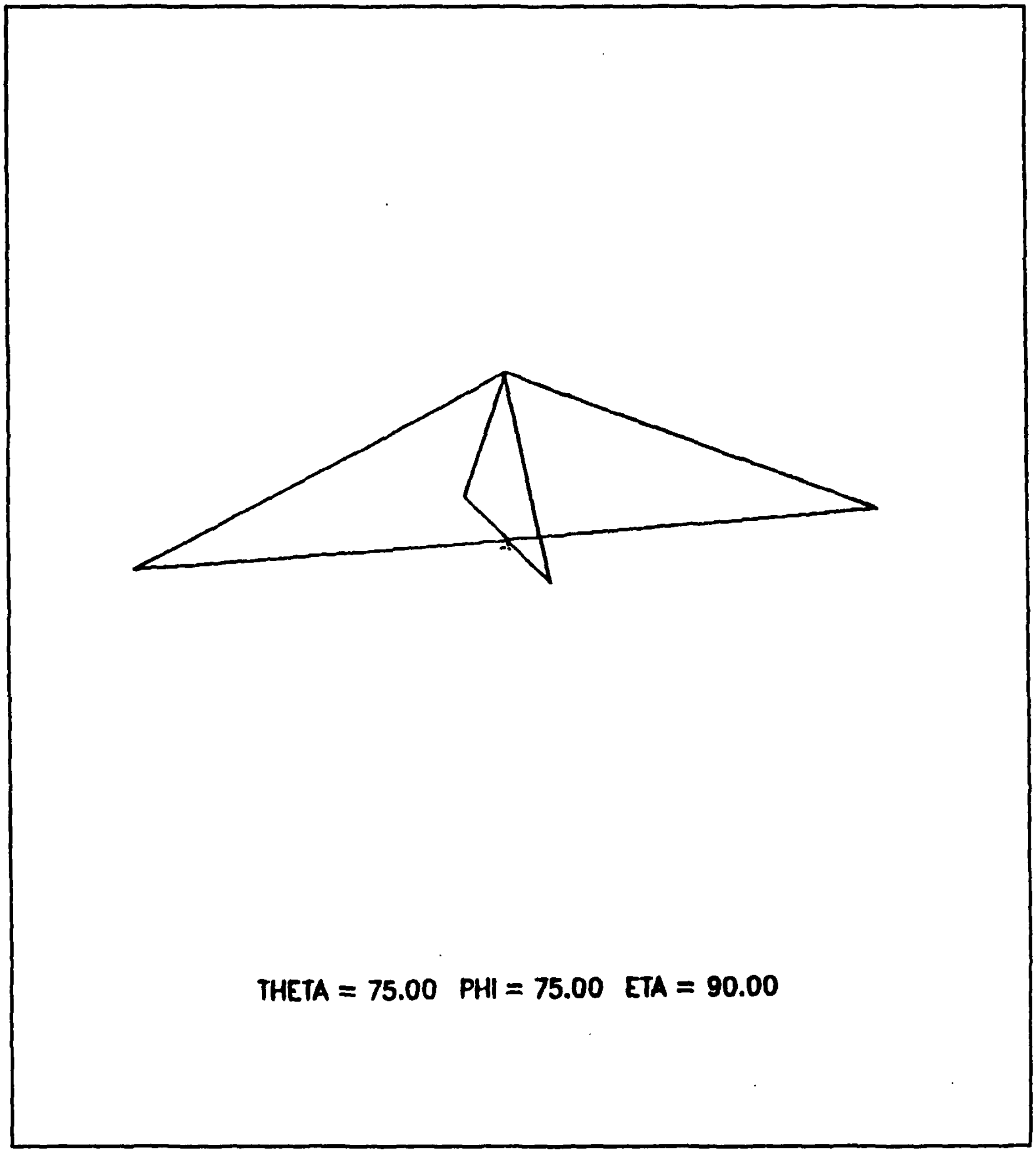

Figure 1. The Army Lowband Double Delta Antenna from TM 11-486-6

3. Top loading : 600 ohms
4. Frequency : 8 to 30 MHz
5. Arm height : 3 feet

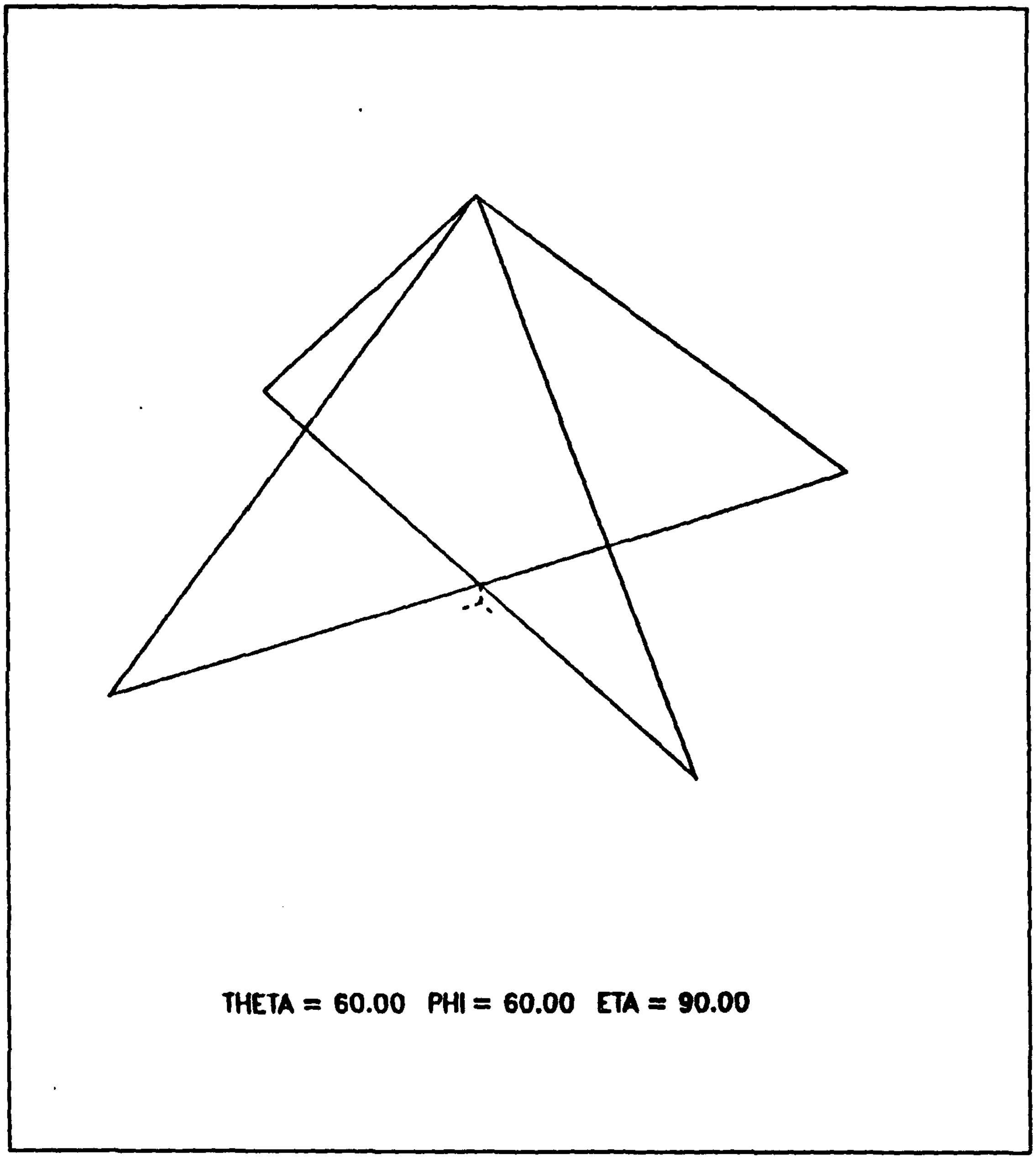

Figure 2. The Army Highband Double Delta Antenna from TM 11-486-6

3. The Air Force Lowband Double Delta Antenna

Figure 3 shows the NEC wire model of the Air Force Lowband DD antenna from the AFCS memo of April 8, 1979. The antenna consists of two identical delta an-

tennas, installed at an angle of 60 degrees (and/or 120 degrees) to each other [Ref. 5]. The following parameters specify the Air Force Lowband Double Delta antenna :

1. Four symmetric arms :100 feet each
2. Top height : 33 feet
3. Top loading : 600 ohms
4. Frequency : 2 to 8 MHz
5. Arm height : 5 feet

4. The Air Force Highband Double Delta Antenna

Figure 4 shows the highband version of the Air Force Double Delta, and the similarity to the Air Force lowband model. The parameters are :

1. Four symmetric arms : 50 feet each
2. Top height : 33 feet.
3. Top loading : 600 ohms
4. Frequency : 8 to 30 MHz
5. Arm height : 5 feet

5. The ESI 32A2A Broadband DD Antenna

Figure 5 depicts the ESI 32A2A Broadband Double Delta antenna from Electrospace Systems Incorporated. The antenna consists of two separate delta antennas, installed at 60 degrees to each other. This antenna is tapered at four of the side angles. The wires are terminated at the apex in a resistive load equal to the wire's characteristic impedance which ensures omnidirectional radiation patterns at an angle near the zenith [Ref. 6]. The specifications of the ESI 32A2A Broadband Double Delta antenna are :

1. Four slanting symmetric arms : 75.08 feet each
2. Top height : 76.54 feet
3. Top loading : 600 ohms
4. Frequency : 2 to 30 MHz
5. Arm height : 9.71 feet

B. COMPUTER MODELS

The antennas were modeled on the IBM system 3033 main-frame computer by using the Numerical Electromagnetics Code (NEC).

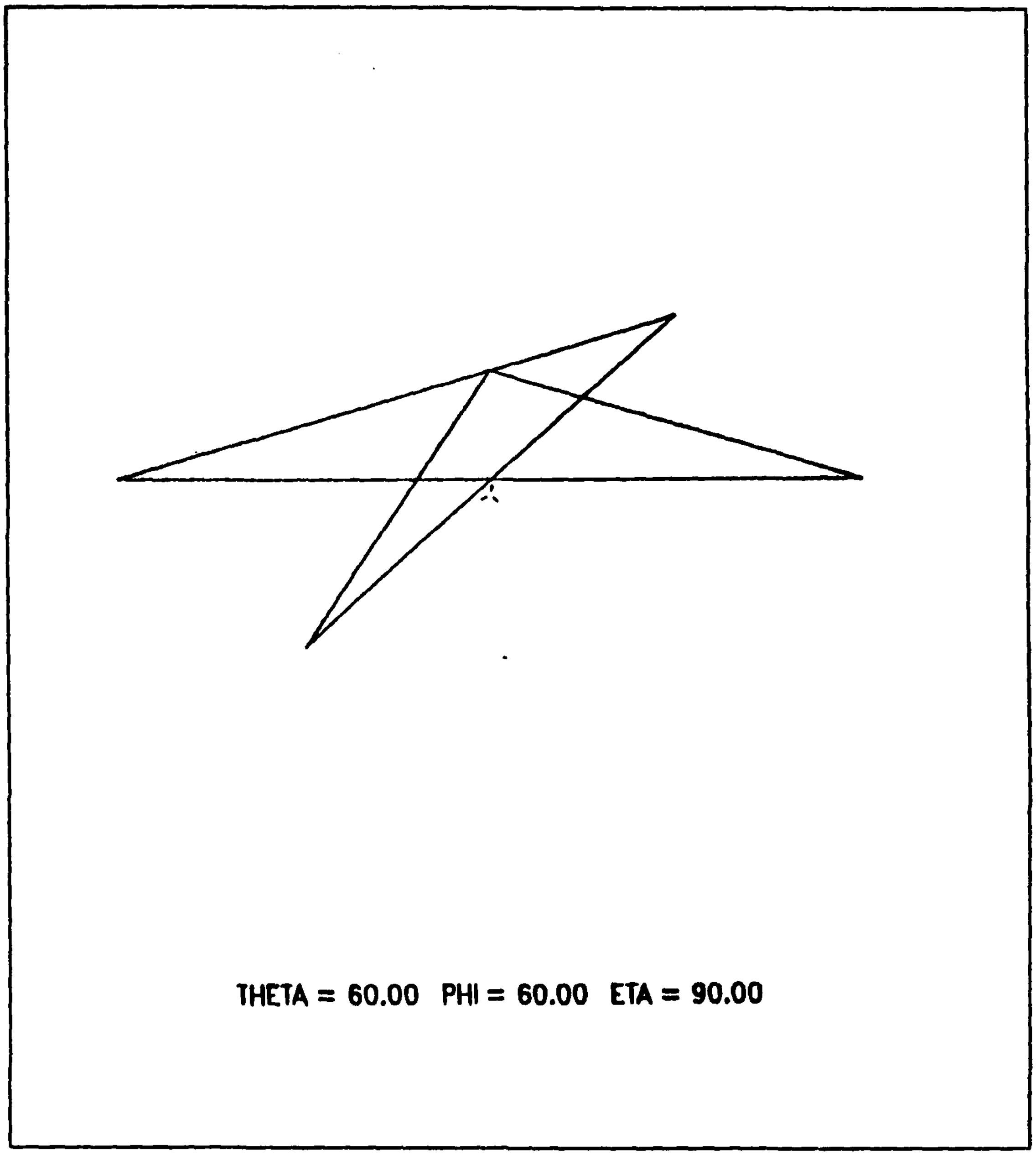

Figure 3. The Air Force Lowband DD Antenna from AFCS Memo 08 April, 1979

The data sets which describe the structures and request computation of structure characteristics are arranged in files made up of card images (comment cards, geometry cards and control cards). Appendix B shows the data sets used in this study. The following cards play a specific role in the computation analysis :

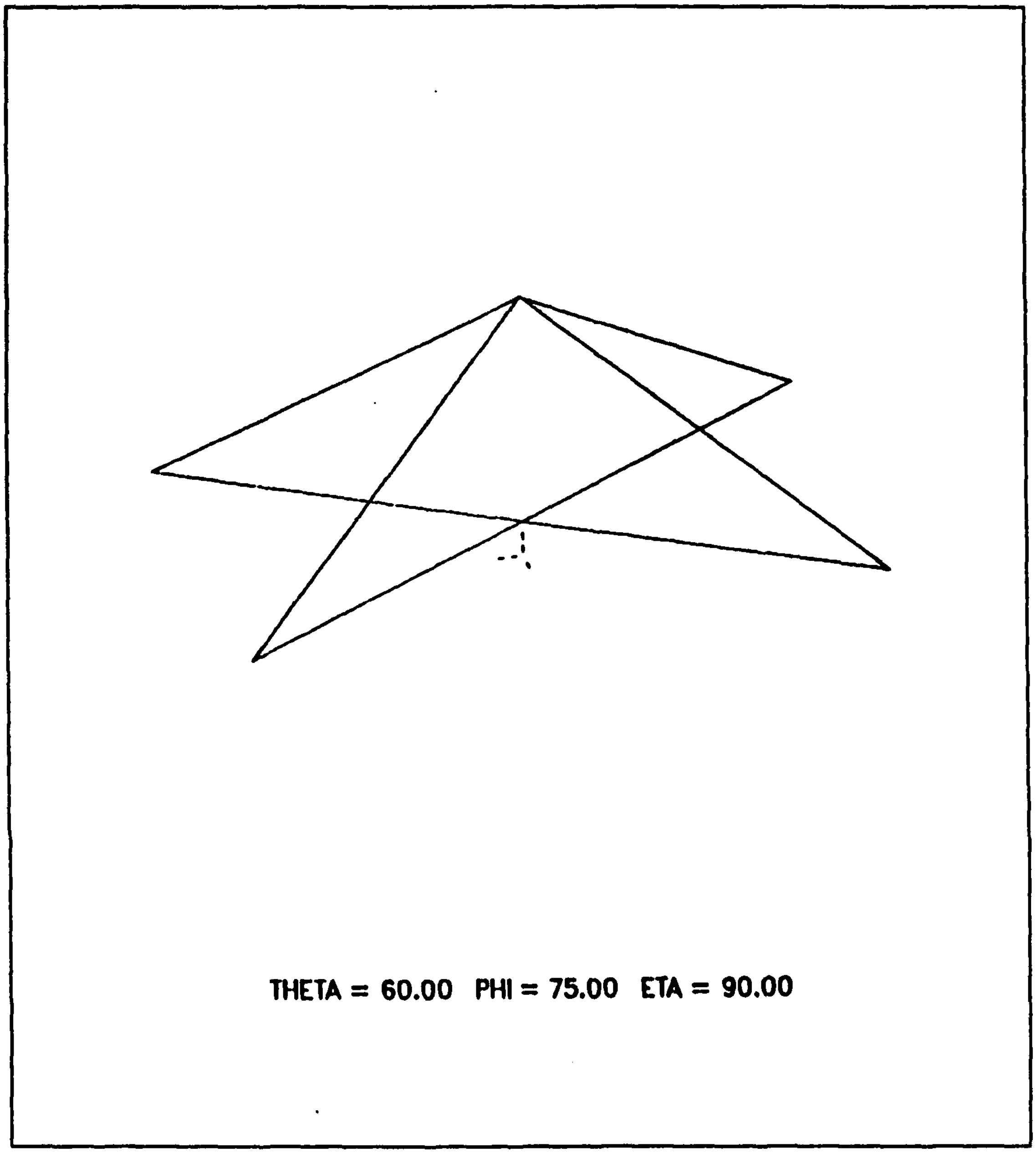

Figure 4. The Air Force Highband DD Antenna from the AFCS Memo of 08 April, 1979

1. GN cards specify the relative dielectric constant and conductivity of the ground in the vicinity of the antenna.
2. PL cards set flags for writing selected output data into a predesignated file for later plotting of the currents, near fields, patterns, impedance, admittance & VSWR.

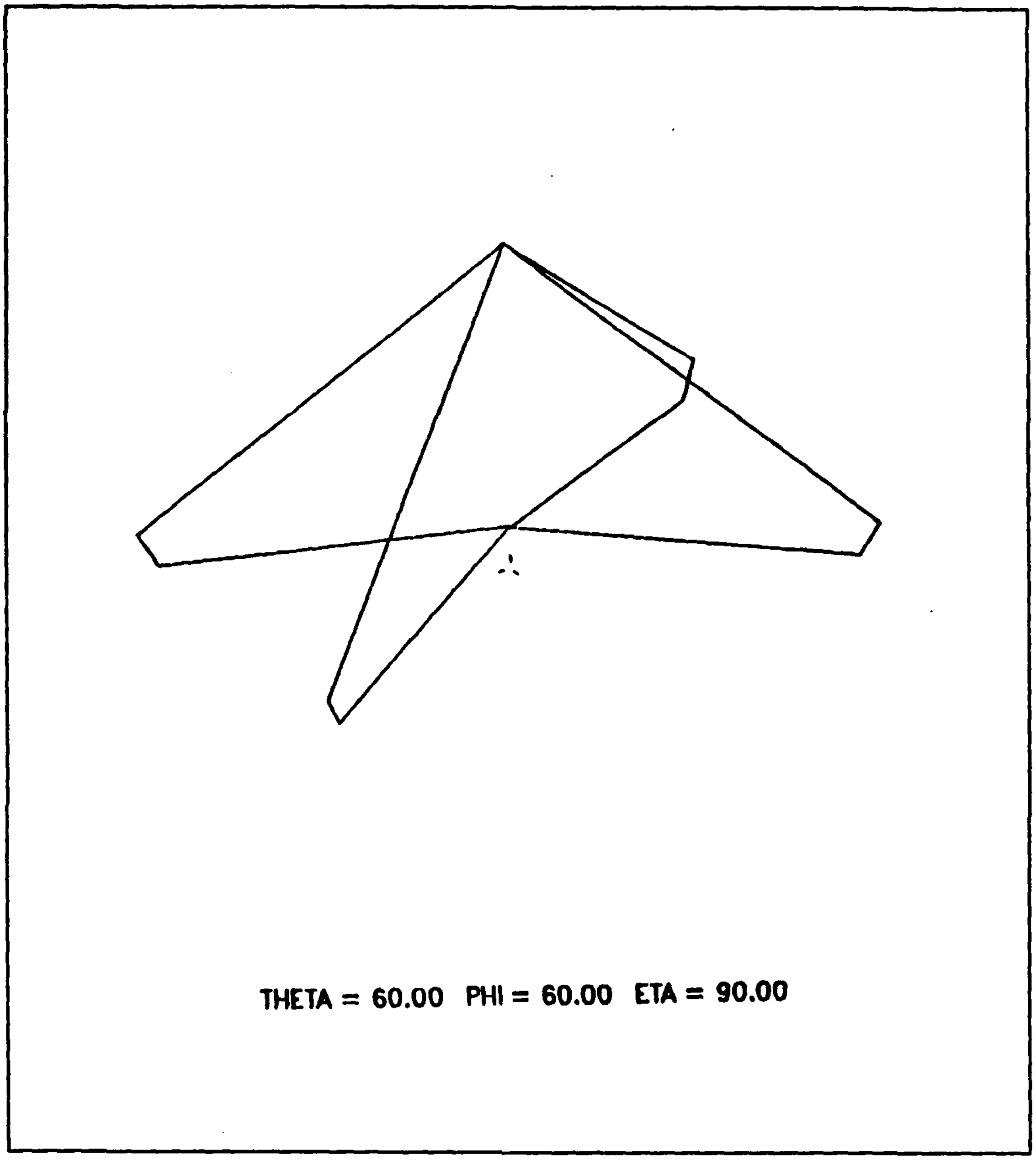

Figure 5. The ESI 32A2A Broadband DD Antenna from Electrospace Systems Incorporated.

3. RP cards specify radiation pattern sampling parameters and cause program execution.

C. STUDY PARAMETERS

Since the performance of an antenna is determined by its characteristic parameters, this study investigates the input impedance and VSWR. Radiation patterns are also valuable for evaluating the performance of an antenna and are investigated as well.

The data sets for computer models of the Double Delta antennas described in Section A are given in Appendix B. Computations of input impedance and VSWR referenced to normalizing impedances of 50, 300 and 600 ohms are done over perfectly conducting ground.

Data sets which are used for the antenna gain power pattern over perfectly conducting ground are in Appendix B. Antenna gain radiation patterns were also calculated over fair ground conditions using the Sommerfeld method for the elevation and azimuth planes. The vertical gain elevation pattern is computed for 91 points of θ at ϕ equal 0 degrees and 91 points of θ at ϕ equal 90 degrees. The horizontal gain azimuth pattern is computed for 91 points of ϕ at θ equal 70, 50, 30, and 10 degrees respectively.

III. PERFORMANCE PARAMETERS OF DOUBLE DELTA ANTENNAS

As described in the previous chapter, the Double Delta antennas from the US Army and the US Air Force, both for lowband and highband, and the ESI 32A2A Broadband DD antenna from Electrospace Systems Inc. were modeled on the IBM Computer using a special program, the Numerical Electromagnetics Code (NEC). A single precision version of NEC was found adequate with respect to accuracy and was used throughout the simulation process. This chapter presents the results given by running the data sets of Appendix B.

A. THE ARMY DOUBLE DELTA ANTENNA

1. Lowband version

This antenna has unsymmetric arms. The long arms provide effective gain for low-frequency use. The unsymmetric arms of this antenna will force different elevation patterns for the two positions, which we label broadside (perpendicular to the long side) and boresight.

a. Input Impedance and VSWR

This antenna has reasonably flat input impedance within the frequency range for normalized impedance equal to 300, or 600 ohms. For 50 ohms the input impedance varies excessively. The value of VSWR varies with frequency, but is acceptable at specific frequencies depending on the normalization impedance, 50, 300, or 600 ohms. Tables 1, 2, and 3 show the input impedance and VSWR for the Army Lowband DD antenna over perfect ground using normalizing impedances equal to 50, 300, and 600 ohms, respectively.

Table 1. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 50 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	179.8 + j93.3	3.59 + j1.86	4.62
3	113.6 - j95.8	2.27 - j1.91	4.08
4	55.16 + j22.86	1.10 + j0.45	1.56
5	59.13 + j23.24	1.18 + j0.46	1.58
6	411.4 + j122.8	8.22 + j2.45	8.97
7	113.06 - j73.94	2.26 - j1.47	3.37
8	110.87 + j97.01	2.21 + j1.94	4.12

Table 2. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 300 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	179.8 + j93.26	0.60 + j0.30	1.9
3	113.6 - j95.8	0.37 - j0.32	2.95
4	55.16 + j22.86	0.18 + j0.07	5.47
5	59.13 + j23.24	0.20 + j0.07	5.11
6	411.4 + j122.8	1.37 + j0.41	1.60
7	113.06 - j73.94	0.37 - j0.25	2.84
8	110.87 + j97.01	0.37 + j0.32	3.03

Table 3. IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 600 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	179.8 + j93.26	0.30 + j0.15	3.43
3	113.6 - j95.8	0.19 - j0.16	5.42
4	55.16 + j22.86	0.09 + j0.03	10.89
5	59.13 + j23.24	0.10 + j0.03	10.16
6	411.4 + j122.8	0.68 + j0.20	1.57
7	113.06 - j73.94	0.18 - j0.13	5.39
8	110.87 + j97.01	0.18 + j0.16	5.56

b. Radiaton Patterns

The radiation patterns are computed for elevation and azimuth planes over perfect and fair ground for each frequency within the frequency range. Elevation patterns are provided both for boresight and broadside.

Over perfect ground and fair ground, for 2 to 4 MHz, the direction of the maximum intensity of radiation is vertical. Above 4 MHz the maximum shifts to an elevation angle less than 90 degrees. But at 8 MHz, the direction of maximum radiation reverts back to a 90 degree elevation angle (boresight). For the broadside case, the antenna radiates toward the vertical. It shows the characteristics of an NVIS (near vertical incidence) antenna. Overall attenuation is present in the fair ground pattern shapes compared to perfect ground. In general, this antenna at the lowest frequency (2 MHz), has a minimum antenna gain greater than -10 dBi. Tables 4 and 5 show the maximum gain versus frequency for the Army Lowband DD Antenna, for perfect ground and fair ground.

Table 4. POWER GAIN VS FREQUENCY FOR THE ARMY LOWBAND DD ANTENNA (BORESIGHT)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	4.0	90	-5.0	90
3	6.0	90	-2.0	90
4	5.0	90	-4.0	90
5	2.5	50	-4.0	45
6	4.0	55	-1.8	52.5
7	3.0	60	-2.8	60
8	3.0	65	0	90

Table 5. POWER GAIN VS FREQUENCY FOR THE ARMY LOWBAND DD ANTENNA (BROADSIDE)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	4.0	90	-5.2	90
3	5.5	90	-2.0	90
4	5.0	90	-4.0	90
5	-2.0	90	-5.0	90
6	1.8	90	-3.0	90
7	-1.8	90	-3.0	90
8	-3.5	90	0	90

2. Highband version

This is a symmetric double delta antenna, modified from the lowband-version by shortening the long arm lengths. It is designed for operation during the high frequency portion of the solar cycle. This antenna provides the same vertical pattern for both broadside and endfire (boresight).

a. Input Impedance and VSWR

A broadband input impedance is achieved by using a normalized impedance equal to the load of 600 ohms. A normalized impedance of 300 ohms provides an acceptable VSWR for most frequencies within the frequency range. For 50 or 600 ohms, the VSWR is unacceptable over most of the HF band. Tables 6, 7, and 8 show the input

impedance and VSWR for the Army Highband DD Antenna using normalized impedances equal to 50, 300, and 600 ohms respectively.

Table 6. IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY HIGHBAND ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 50 OHMS)

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
8	162 + j6.54	2.53 + j0.13	2.54
9	293 - j25.7	5.86 -j0.51	5.90
10	95.2 -j83.4	1.90 - j1.67	3.61
11	60.3 + j30.2	1.21 + j0.60	1.77
12	112 + j155	224 + j3.11	6.85
13	391 + j51.4	7.83 + j1.03	7.96
14	170 - j30.7	3.39 - j0.61	3.51
15	235 + j61.7	4.71 + j1.23	5.05
16	221 - j132	4.43 - j2.65	6.07
17	82 - j49.1	1.64 - j0.98	2.42
18	84.6 + j54.5	1.69 + j1.09	2.60
19	177 + j90.1	3.54 + j1.80	4.52
20	164 + j48.7	3.28 + j0.97	3.6
21	191 + j130	3.83 + j2.60	5.67
22	419 - j0.64	8.39 - j1.30	8.39
23	149 - j132	2.98 - j2.65	5.49
24	92 - j11.3	1.84 - j0.226	1.88
25	143 + j39.4	2.86 + j0.788	3.10
26	119 + j19.10	2.39 + j0.382	2.46
27	104 + j97.60	2.08 + j1.95	4.15
28	212 + j192	4.24 + j3.85	7.84
29	376 - j31.5	7.52 - j0.63	7.58
30	173 - j59	3.45 - j1.18	3.89

Table 7. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY HIGHBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 300 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
8	162 + j6.54	0.42 + j0.02	2.37
9	293 - j25.7	0.97 -j0.08	1.09
10	95.2 -j83.4	0.32 - j0.27	3.42
11	60.3 + j30.2	0.20 + j0.10	5.03
12	112 + j155	0.37 + j0.51	3.48
13	391 + j51.4	1.30 + j0.17	1.36
14	170 - j30.7	0.56 - j0.10	1.81
15	235 + j61.7	0.78 + j0.20	1.40
16	221 - j132	0.73 - j0.44	1.80
17	82 - j49.1	0.27 - j0.16	3.77
18	84.6 + j54.5	0.28 + j0.18	3.67
19	177 + j90.1	0.59 + j0.30	1.92
20	164 + j48.7	0.54 + j0.16	1.9
21	191 + j130	0.63 + j0.43	2.0
22	419 - j0.64	1.40 - j0.002	1.40
23	149 - j132	0.49 - j0.44	2.51
24	92 - j11.3	0.30 - j0.037	3.27
25	143 + j39.4	0.47 + j0.13	2.14
26	119 + j19.10	0.39 + j0.63	2.53
27	104 + j97.60	0.34 + j0.32	3.23
28	212 + j192	0.70 + j0.64	2.26
29	376 - j31.5	1.25 - j0.10	1.28
30	173 - j59	0.57 - j0.20	1.84

Table 8. IMPEDANCE AND VSWR VS FREQUENCY FOR THE ARMY HIGHBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 600 OHMS)

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
8	162 + j6.54	0.21 + j0.01	4.74
9	293 - j25.7	0.48 -j0.04	2.05
10	95.2 -j83.4	0.16 - j0.14	6.43
11	60.3 + j30.2	0.10 + j0.05	9.97
12	112 + j155	0.18 + j0.25	5.72
13	391 + j51.4	0.65 + j0.09	1.55
14	170 - j30.7	0.28 - j0.05	3.55
15	235 + j61.7	0.39 + j0.10	2.58
16	221 - j132	0.37 - j0.22	2.86
17	82 - j49.1	0.14 - j0.08	7.37
18	84.6 + j54.5	0.14 + j0.09	7.15
19	177 + j90.1	0.29 + j0.15	3.48
20	164 + j48.7	0.27 + j0.08	3.68
21	191 + j130	0.32 + j0.23	3.3
22	419 - j0.64	0.70 - j0.001	1.43
23	149 - j132	0.25 - j0.22	4.24
24	92 - j11.3	0.15 - j0.018	6.52
25	143 + j39.4	0.24 + j0.07	4.22
26	119 + j19.10	0.19 + j0.32	5.03
27	104 + j97.60	0.17 + j0.16	5.93
28	212 + j192	0.35 + j0.32	3.16
29	376 - j31.5	0.65 - j0.05	1.60
30	173 - j59	0.28 - j0.10	3.51

b. Radiation Patterns

The radiation patterns over perfectly conducting and fair ground (real, lossy ground) for this antenna show that the direction of maximum intensity of radiation for a frequency range of 8 MHz to 24 MHz occurs at an elevation angle of 90 degrees, even though the lobe begins to split into several smaller lobes before 20 MHz. Above 24 MHz, the direction of maximum intensity of radiation shifts to an angle less than 90

degrees elevation angle. Tables 9 and 10 show the maximum gain for the Army Highband DD Antenna.

Table 9. POWER GAIN VS FREQUENCY FOR THE ARMY HIGHBAND DD ANTENNA (BORESIGHT)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation dBi
8	0.4	90	-0.3	90
9	4.0	90	1.1	90
10	7.0	90	1.4	90
11	8	90	1.2	90
12	7.8	90	0.7	90
13	5.5	90	-0.6	90
14	1.6	35	-3.5	90
15	1.8	52.5	-3.8	50
16	4.6	90	-2.1	90
17	8.8	90	0.9	90
18	10	90	3.2	90
19	9.0	90	3.2	90
20	5.9	90	2.2	90
21	4.4	90	0.9	90
22	7.4	90	1.8	90
23	8.4	90	2.3	90
24	8.4	90	1.0	90
25	4.8	90	-1.0	37.5
26	5.0	72.5	-0.9	37.5
27	7.0	64	-1.0	37.5
28	8.4	74	0	74
29	7.6	74	0.1	74
30	4.8	75	-0.8	75

Table 10. POWER GAIN VS FREQUENCY FOR THE ARMY HIGHBAND DD ANTENNA (BROADSIDE)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
8	0.4	90	-0.3	90
9	4.0	90	1.1	90
10	7.0	90	1.4	90
11	8	90	1.2	90
12	7.8	90	0.7	90
13	5.5	90	-0.6	90
14	1.6	35	-3.5	90
15	1.8	52.5	-3.8	50
16	4.6	90	-2.1	90
17	8.8	90	0.9	90
18	10	90	3.2	90
19	9.0	90	3.2	90
20	5.9	90	2.2	90
21	4.4	90	0.9	90
22	7.4	90	1.8	90
23	8.4	90	2.3	90
24	8.4	90	1.0	90
25	4.8	90	-1.0	37.5
26	5.0	72.5	-0.9	37.5
27	7.0	64	-1.0	37.5
28	8.4	74	0	74
29	7.6	74	0.1	74
30	4.8	75	-0.8	75

B. THE AIR FORCE DOUBLE DELTA ANTENNA

1. Lowband version

This antenna is symmetric and has long arms which provide the effective gain over the low-frequency range. The antenna consists of two deltas at an angle of 60 degrees to each other. Therefore, it has different patterns for broadside and endfire (boresight).

a. Input Impedance and VSWR

The broadband impedance characteristics are achieved by using a normalized impedance equal to the load of 600 ohms. For a normalized impedance of 300 ohms, the input impedance is reasonably flat for all frequencies within the frequency range. For 50 ohms, the input impedance varies substantially. The VSWR is very good for for 300 and 600 ohm normalized feedpoint impedances. The maximum is 2.3:1 with the average being 1.65:1 for 600 ohms, and the maximum value equal to 2.01:1 with an average value of 1.6:1 for 300 ohms. For 50 ohms, the VSWR is greater than 5:1 for all frequencies. Tables 11, 12, and 13 show the input impedance and VSWR for the Air Force Double Delta antenna.

Table 11. IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 50 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	400 + j187	8.0 + j3.70	9.78
3	381 + j8.87	7.62 + j0.18	7.63
4	493 + j122	9.86 + j2.44	1.05
5	481 - j201	9.61 - j4.02	11.3
6	262 - j28.4	5.23 - j0.56	5.29
7	395 + j129	7.90 + j2.577	8.75
8	448 + j13.4	8.96 + j0.26	8.97

Table 12. IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 300 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	400 + j187	1.33 + j0.62	1.83
3	381 + j8.87	1.27 + j0.03	1.27
4	493 + j122	1.64 + j0.41	1.80
5	481 - j201	1.60 - j0.67	2.01
6	262 - j28.4	0.87 - j0.09	1.19
7	395 + j129	1.32 + j0.42	1.58
8	448 + j13.4	1.49 + j0.04	1.50

Table 13. IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE LOWBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 600 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	400 + j187	0.66 + j0.31	1.74
3	381 + j8.87	0.64 + j0.01	1.58
4	493 + j122	0.82 + j0.20	1.35
5	481 - j201	0.80 - j0.35	1.54
6	262 - j28.4	0.43 - j0.04	2.30
7	395 + j129	0.65 + j0.21	1.64
8	448 + j13.4	0.75 + j0.02	1.34

b. Radiation Patterns

For both perfectly conducting and fair ground conditions, this antenna has the major lobe maximum at an elevation angle of 90 degrees from 2 to 7 MHz. At 8 MHz, the direction of maximum radiation shifts to an angle less than 90 degrees (boresight). For broadside azimuth, the direction of maximum radiation is vertical for all frequencies within the band. Antenna gain for the lowest frequency (2 MHz) is very small, less than -10 dBi. Tables 14 and 15 show the maximum gain for the Air Force Lowband Double Delta Antenna.

Table 14. POWER GAIN VS FREQUENCY FOR THE AIR FORCE LOWBAND DD ANTENNA (BORESIGHT)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	-17	90	-17.4	90
3	-8.2	90	-8.3	90
4	-4.2	90	-4.5	90
5	-1.9	90	-3.0	90
6	-2.2	90	-3.0	90
7	-4.4	90	-5.5	90
8	-0.2	45	-3.5	40

Table 15. **POWER GAIN VS FREQUENCY FOR THE AIR FORCE LOWBAND DD ANTENNA (BROADSIDE)**

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	-16	90	-17.5	90
3	-8.2	90	-8.3	90
4	-4.2	90	-4.3	90
5	-2.1	90	-3.0	90
6	-2.2	90	-3.0	90
7	-4.4	90	-5.5	90
8	-7.2	90	-10.0	90

2. Highband version

This antenna is exactly the same as the low-frequency version, except the arms are shorter, providing useful gain over the high frequency band.

a. Input Impedance and VSWR

This antenna, like its lowband relative, has smooth input impedance for 600 ohms normalized impedance, acceptable values for 300, ohms and widely variable impedances for 50 ohms. The values of VSWR follow the same trend as input impedance. The maximum value is 2.33:1 with an average value of 1.6:1 for normalized impedance of 300 ohms, 2.51:1 with an average value equal to 1.7:1 for 600 ohms, and at 50 ohms values greater than 5:1 for any frequency. Tables 16, 17, and 18 show the impedance and VSWR for the Air Force Highband Double Delta antenna.

Table 16. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE HIGHBAND ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 50 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
8	530 + j127	10.6 + j2.55	11.2
9	612 - j93.1	12.2 - j1.86	12.5
10	401 - j198	8.03 - j3.96	10.0
11	268 - j96.1	5.36 - j1.92	6.07
12	251 + j31.9	5.03 + j0.63	5.11
13	328 + j124	6.56 + j2.48	7.52
14	430 + j91.2	8.59 + j1.82	8.99
15	401 + j31.8	8.03 + j0.63	8.08
16	372 + j76.4	7.43 + j1.53	7.75
17	440 + j131	8.79 + j2.62	9.58
18	565 + j44.0	11.3 + j0.88	11.4
19	473 - j137	9.47 - j2.75	10.3
20	306 - j102	6.11 - j2.04	6.81
21	258 + j11.0	5.17 + j0.22	5.18
22	302 + j91.9	6.04 + j1.84	6.62
23	358 + j81.4	7.16 + j1.63	7.50
24	326 + j63.1	6.52 + j1.26	6.77
25	297 + j130	5.94 + j2.60	7.11
26	362 + j232	7.23 + j4.65	10.3
27	580 + j232	11.6 + j4.64	13.5
28	620 - j105	12.4 - j2.10	12.8
29	341 - j149	6.82 - j2.98	8.14
30	239 - j15.5	4.78 - j0.31	4.80

Table 17. IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE HIGHBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 300 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
8	530 + j127	1.77 + j0.42	1.91
9	612 - j93.1	2.04 - j0.31	2.10
10	401 - j198	1.34 - j0.65	1.88
11	268 - j96.1	0.89 - j0.32	1.43
12	251 + j31.9	0.84 + j0.10	1.24
13	328 + j124	1.09 + j0.41	1.50
14	430 + j91.2	1.43 + j0.30	1.55
15	401 + j31.8	1.34 + j0.10	1.36
16	372 + j76.4	1.24 + j0.255	1.37
17	440 + j131	1.47 + j0.43	1.68
18	565 + j44.0	1.88 + j0.15	1.90
19	473 - j137	1.58 - j0.45	1.78
20	306 - j102	1.02 - j0.34	1.40
21	258 + j11.0	0.86 + j0.04	1.17
22	302 + j91.9	1.01 + j0.30	1.36
23	358 + j81.4	1.19 + j0.27	1.36
24	326 + j63.1	1.09 + j0.21	1.24
25	297 + j130	0.99 + j0.43	1.54
26	362 + j232	1.21 + j0.77	2.04
27	580 + j232	1.93 + j0.77	2.33
28	620 - j105	2.07 - j0.35	2.14
29	341 - j149	1.14 - j0.49	1.61
30	239 - j15.5	0.79 - j5.16	1.26

Table 18. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE AIR FORCE HIGHBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 600 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
8	530 + j127	0.88 + j0.21	1.29
9	612 - j93.1	1.02 - j0.15	1.17
10	401 - j198	0.66 - j0.33	1.76
11	268 - j96.1	0.45 - j0.16	2.31
12	251 + j31.9	0.42 + j0.05	2.39
13	328 + j124	0.55 + j0.21	1.94
14	430 + j91.2	0.71 + j0.15	1.46
15	401 + j31.8	0.67 + j0.05	1.50
16	372 + j76.4	0.62 + j0.13	1.66
17	440 + j131	0.73 + j0.22	1.49
18	565 + j44.0	0.94 + j0.07	1.10
19	473 - j137	0.79 - j0.23	1.42
20	306 - j102	0.51 - j0.17	2.04
21	258 + j11.0	0.43 + j0.02	2.32
22	302 + j91.9	0.50 + j0.15	2.05
23	358 + j81.4	0.60 + j0.13	1.72
24	326 + j63.1	0.55 + j0.11	1.87
25	297 + j130	0.49 + j0.22	2.14
26	362 + j232	0.61 + j0.38	2.02
27	580 + j232	0.95 + j0.38	1.48
28	620 - j105	1.04 - j0.17	1.19
29	341 - j149	0.57 - j0.24	1.91
30	239 - j15.5	0.39 - j2.58	2.51

b. Radiation Patterns

Zenith-directed radiation occurs from 8 to 13 MHz; above 13 MHz, the elevation angle for maximum radiation drops below 90 degrees (boresight). In the broadside case, the 90 degree elevation angle holds for all frequencies (8 to 30 MHz). The beam begins to split into several smaller lobes above 25 MHz. Tables 19 and 20 show the maximum gain for the Air Force Highband Double Delta antenna.

Table 19. **POWER GAIN VS FREQUENCY FOR THE AIR FORCE HIGHBAND DD ANTENNA (BORESIGHT)**

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
8	0	90	-1.0	90
9	0.65	90	-0.2	90
10	0.6	90	-0.15	90
11	0	90	-0.6	90
12	-1.2	90	-1.4	90
13	-3.0	90	-2.6	90
14	-0.8	35	-2.4	90
15	0.85	35	-1.0	30
16	2.4	40	0.3	40
17	2.8	40	1.10	40
18	2.8	45	1.8	40
19	2.6	47.5	1.4	45
20	2.2	52.5	1.1	50
21	2.4	55	1.2	55
22	4.0	60	2.2	57.5
23	4.3	60	2.8	60
24	4.8	62.5	2.8	60
25	4.9	22.5	2.2	22.5
26	6.8	25	3.8	22.5
27	7.0	27.5	4.8	27.5
28	6.8	30	4.6	30
29	5.3	37.5	4.0	35
30	6.8	42.5	4.2	40

Table 20. **POWER GAIN VS FREQUENCY FOR THE AIR FORCE HIGHBAND DD ANTENNA (BROADSIDE)**

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
8	0	90	-1.0	90
9	0.40	90	-0.2	90
10	0.45	90	-0.15	90
11	0	90	-0.6	90
12	-1.2	90	-1.4	90
13	-3.5	90	-2.4	90
14	-4.0	90	-3.0	90
15	-3.20	90	-2.8	90
16	-2.8	90	-3.0	90
17	-2.6	90	-2.8	90
18	-2.0	90	-2.4	90
19	-1.2	90	-2.4	90
20	0	90	-2.0	90
21	0.4	90	-1.4	90
22	0.15	90	-1.4	90
23	-0.35	90	-1.6	90
24	-0.9	90	-1.6	90
25	0	90	-1.2	90
26	1.2	90	-0.25	90
27	2.4	90	0.3	90
28	2.4	90	0.3	90
29	1.4	90	-0.9	90
30	-0.95	90	-3.8	90

C. THE ESI 32A2A DOUBLE DELTA ANTENNA

This is a broadband double delta antenna. The configuration and height above ground of this antenna were selected to provide maximum radiation near the zenith for lowband-frequencies. It has a different pattern for boresight and broadside due to the 60 degree angle between the two delta loops.

a. Input Impedance and VSWR

The input impedance of this antenna is maximally flat for 600 ohm normalization. Typical 300 and 50 ohm results occur similar to the other DD antennas. The maximum value of VSWR is 2.63:1 with an average value of 1.5:1 for 300 ohms. A maximum value of 2.36:1 with an average of 1.7:1 for 600 ohms. For 50 ohms, the value of VSWR is greater than 5:1 for all frequencies. Tables 21, 22 and 23 show the input impedance and VSWR for the ESI 32A2A Broadband Double Delta antenna.

b. Radiation Patterns

For perfect and fair ground conditions, below 7 MHz, the direction of maximum radiation is vertical. Above a frequency of 7 MHz, the lobe begins to split into smaller lobes, and the angle drops below 90 degrees (boresight). In the broadside case, the direction of maximum radiation is vertical from 2 to 19 MHz. At 9 MHz the beam begins typical small-lobe formation. Above 19 MHz the elevation angle of the lobe drops. For the lowest frequency (2 MHz), the antenna gain is less than -10 dBi. Tables 24 and 25 show the maximum gain for the ESI 32A2A Broadband Double Delta antenna in both perfect and fair ground conditions.

Table 21. **IMPEDANCE AND VSWR VS FREQUENCY FOR THE ESI 32A2A BROADBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 50 OHMS)**

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
2	365 + j57.10	7.31 + j1.14	7.49
3	332 - j4.03	6.64 - j0.08	6.64
4	362 + j194	7.24 + j3.89	9.36
5	778 + j80.8	15.6 + j1.62	15.7
6	444 - j193	8.87 - j3.87	10.6
7	427 - j36.3	8.55 - j0.72	8.61
8	371 - j148	7.43 - j2.96	8.63
9	255 + j23.5	5.10 + j0.47	5.15
10	460 + j196	9.19 + j3.92	10.9
11	494 - j125	9.87 - j2.50	10.5
12	366 + j32.5	7.32 + j0.65	7.38
13	572 - j61.4	11.4 - j1.23	11.6
14	291 - j132	5.81 - j2.26	7.04
15	299 + j95.6	5.97 + j1.91	6.60
16	496 - j24.1	9.92 - j0.48	9.94
17	307 - j8.86	6.14 - j0.17	6.15
18	430 + j130	8.61 + j2.60	9.41
19	458 - j117	9.15 - j2.23	9.76
20	299 + j7.14	5.97 + j0.14	5.98
21	447 + j40.2	8.94 + j0.80	9.01
22	320 - j52.2	6.39 - j1.04	6.57
23	321 + j97.4	6.43 + j1.95	7.03
24	454 + j10.8	9.09 + j0.22	9.09
25	302 + j10.4	6.04 + j0.21	6.05
26	411 + j138	8.21 + j2.75	9.15
27	423 - j90.0	8.46 - j1.80	8.84
28	275 + j27.6	5.51 + j0.55	5.57
29	396 + j77.2	7.92 + j1.54	8.22
30	301 - j9.58	6.03 - j0.19	6.03

Table 22. IMPEDANCE AND VSWR VS FREQUENCY FOR THE ESI 32A2A BROADBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 300 OHMS)

Freq.	Impedance (un-normalized)	Impedance (nor-malized)	VSWR
2	365 + j57.10	1.22 + j0.19	1.30
3	332 - j4.03	1.11 - j0.013	1.11
4	362 + j194	1.21 + j0.64	1.84
5	778 + j80.8	2.59 + j0.27	2.63
6	444 - j193	1.48 - j0.64	1.91
7	427 - j36.3	1.42 - j0.12	1.44
8	371 - j148	1.24 - j0.49	1.63
9	255 + j23.5	0.85 + j0.07	1.20
10	460 + j196	1.53 + j0.65	1.95
11	494 - j125	1.65 - j0.42	1.80
12	366 + j32.5	1.22 + j0.11	1.25
13	572 - j61.4	1.91 - j0.20	1.94
14	291 - j132	0.96 - j0.44	1.56
15	299 + j95.6	0.99 + j0.32	1.37
16	496 - j24.1	1.65 - j0.08	1.66
17	307 - j8.86	1.02 - j0.03	1.04
18	430 + j130	1.43 + j0.43	1.66
19	458 - j117	1.53 - j0.39	1.69
20	299 + j7.14	0.99 + j0.03	1.02
21	447 + j40.2	1.49 + j0.13	1.51
22	320 - j52.2	1.07 - j0.17	1.20
23	321 + j97.4	1.07 + j0.32	1.38
24	454 + j10.8	1.51 + j0.03	1.52
25	302 + j10.4	1.01 + j0.03	1.04
26	411 + j138	1.37 + j0.46	1.65
27	423 - j90.0	1.41 - j0.30	1.53
28	275 + j27.6	0.91 + j0.09	1.14
29	396 + j77.2	1.32 + j0.26	1.43
30	301 - j9.58	1.00 - j0.03	1.03

Table 23. IMPEDANCE AND VSWR VS FREQUENCY FOR THE ESI 32A2A BROADBAND DD ANTENNA OVER PERFECT GROUND (NORMALIZED IMPEDANCE = 600 OHMS)

Freq.	Impedance (un-normalized)	Impedance (normalized)	VSWR
2	365 + j57.10	0.61 + j0.09	1.67
3	332 - j4.03	0.55 - j0.006	1.81
4	362 + j194	0.60 + j0.32	1.91
5	778 + j80.8	1.28 + j0.13	1.33
6	444 - j193	0.74 - j0.32	1.61
7	427 - j36.3	0.71 - j0.06	1.41
8	371 - j148	0.62 - j0.25	1.77
9	255 + j23.5	0.42 + j0.04	2.36
10	460 + j196	0.76 + j0.33	1.58
11	494 - j125	0.82 - j0.21	1.35
12	366 + j32.5	0.61 + j0.05	1.65
13	572 - j61.4	0.95 - j0.10	1.12
14	291 - j132	0.48 - j0.22	2.19
15	299 + j95.6	0.49 + j0.16	2.08
16	496 - j24.1	0.83 - j0.04	1.22
17	307 - j8.86	0.51 - j0.018	1.95
18	430 + j130	0.71 + j0.22	1.52
19	458 - j117	0.77 - j0.19	1.42
20	299 + j7.14	0.48 + j0.018	2.01
21	447 + j40.2	0.75 + j0.06	1.36
22	320 - j52.2	0.53 - j0.08	1.90
23	321 + j97.4	0.53 + j0.16	1.94
24	454 + j10.8	0.76 + j0.018	1.32
25	302 + j10.4	0.51 + j0.017	1.99
26	411 + j138	0.68 + j0.23	1.60
27	423 - j90.0	0.71 - j0.15	1.48
28	275 + j27.6	0.45 + j0.04	2.18
29	396 + j77.2	0.68 + j0.13	1.56
30	301 - j9.58	0.50 - j0.016	1.99

Table 24. **POWER GAIN VS FREQUENCY FOR THE ESI 32A2A BROADBAND DD ANTENNA (BORESIGHT)**

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	-12.7	90	-15.0	90
3	-5.6	90	-7.5	90
4	-2.0	90	-4.5	90
5	-1.0	90	-2.8	90
6	-2.1	90	-2.8	90
7	-3.95	90	-3.0	90
8	-1.8	30	-3.0	90
9	0.60	32.5	-1.9	30
10	1.1	32.5	-0.45	30
11	-0.56	50	-2.7	35
12	2.60	57.5	0.45	52.5
13	4.80	57.5	1.80	55
14	3.80	57.5	0.95	58
15	4.0	90	1.85	90
16	4.0	90	2.0	90
17	6.0	37.5	2.80	36
18	7.0	40	4.2	37.5
19	7.2	40	4.2	40
20	5.0	65	2.4	60
21	5.6	57.5	3.40	25
22	5.5	27.5	2.60	27.5
23	8.0	27.5	5.2	27.5
24	8.1	30	5.8	27.5
25	5.8	45	4.1	35
26	8.4	42.5	5.6	42.5
27	8.6	42.5	5.0	42.5
28	8.0	57.5	5.4	57.5
29	8.9	57.5	6.8	57.5
30	7.2	57.5	5.4	57.5

Table 25. POWER GAIN VS FREQUENCY FOR THE ESI 32A2A BROADBAND DD ANTENNA (BROADSIDE)

Freq.	Power gain (Perfect gnd) dBi	Elevation angle	Power gain (Fair gnd) dBi	Elevation angle
2	-12.2	90	-15.0	90
3	-5.6	90	-7.5	90
4	-2.0	90	-4.5	90
5	-1.0	90	-2.8	90
6	-0.50	0	-2.8	90
7	-0.60	0	-3.0	90
8	-1.3	0	-3.0	90
9	-2.1	90	-3.2	90
10	-2.6	90	-4	90
11	-2.6	90	-4.6	90
12	-2.80	90	-4.6	90
13	-3.0	90	-4.1	90
14	0.70	90	-0.65	90
15	4.0	90	1.90	90
16	4.0	90	2.0	90
17	2.50	0	-0.30	90
18	3.2	0	-2.4	90
19	2.4	0	-3.0	90
20	1.5	60	-1.4	60
21	2.2	62.5	-0.15	62.5
22	0.60	65	-1.0	65
23	1.2	67.5	-0.65	67.5
24	2.8	62.5	0.30	67.5
25	2.2	40	-1.2	67.5
26	4.4	42.5	0	42.5
27	3.0	42.5	-0.35	42.5
28	0.95	47.5	-1.2	46
29	3.2	47.5	0	47.5
30	3.1	47.5	-0.50	47.5

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis has presented a numerical analysis of the double delta antennas presently used by the US Army, the US Air Force and a commercial model (ESI 32A2A) to obtain performance parameters such as input impedance, VSWR, and radiation patterns.

The results indicate a normalized impedance equal to the terminating load resistance for the antennas provide broadband impedance characteristics within the 2 - 30 MHz frequency range. The VSWR varies excessively for all frequencies for the Army DD antenna, but an acceptable value of VSWR exists for the Air Force and the ESI 32A2A DD antennas by using a normalized impedance equal to 300 or 600 ohms. At 2 MHz, the gain is less than -10 dBi for the Air Force and the ESI DD antennas, but for the Army DD antenna it is greater than -10 dBi. The Army DD antenna provides radiation patterns with the direction of maximum radiation vertical at frequencies below 24 MHz. However, the radiation actually begins to split into smaller lobes at 20 MHz. Above 24 MHz, the direction of maximum radiation shifts to an elevation angle less than 90 degrees. The Air Force DD antenna has radiation patterns with the maximum radiation occuring at 90 degrees elevation for all frequencies. The radiation begins to split into several small lobes at 25 MHz. From 2 to 19 MHz, the ESI 32A2A DD antenna shows radiation patterns with the direction of maximum intensity of radiation occuring at 90 degrees elevation angle, even though the beam begins to split into a several small lobes at 9 MHz. Above 19 MHz, the maximum shifts to an elevation angle less than 90 degrees.

B. RECOMMENDATIONS

This thesis has presented an extensive study of double delta antennas to determine antenna performance parameters such as input impedance, VSWR and antenna gain radiation patterns.

If computer resources become available and if antenna siting conditions warrant it, other ground characteristics can be investigated. Multi-wire elements show broadband performance (they approximate low Q "fat" conductors) and might provide improved performance in VSWR. If omni-directional azimuthal characteristics are desired, the DD model with 60 degree angles between loops could be reconfigured at 90 degrees.

APPENDIX A. THE NUMERICAL ELECTROMAGNETICS CODE (NEC)

A. INTRODUCTION

The Numerical Electromagnetics Code (NEC) is a user-oriented computer code for analysis of the electromagnetic response of antennas and other metal structures. It is built around the numerical solution of integral equations for the current induced on the structure by sources or incident fields. This approach avoids many of the simplifying assumptions required by other solution methods and provides a highly accurate and versatile tool for electromagnetic analysis.

The code combines an integral equation for smooth surfaces with one specialized to wires to provide for convenient and accurate modeling of a wide range of structures. A model may include nonradiating networks and transmission lines connecting parts of the structure, perfect or imperfect conductors, and lumped element loading. A structure may also be modeled over a ground plane that may be either a perfect or imperfect conductor.

The excitation may be either voltage sources on the structure or an incident plane wave of linear or elliptic polarization. The output may include induced currents and charges, near electric or magnetic fields, and radiated fields. Hence the program is suited to either antenna analysis or scattering and EMP studies.

The integral equation approach is best suited to structures with dimensions up to several wavelengths. Although there is no theoretical size limit, the numerical solution requires a matrix equation of increasing order as the structure size is increased relative to a wavelength. Hence, modeling very large structures may require more computer time and file storage than is practical on a particular machine. In such cases standard high-frequency approximations such as geometrical optics, physical optics, or geometrical theory of diffraction may be more suitable than the integral equation approach used in NEC [Ref. 3].

B. STRUCTURE MODELING

The basic devices for modeling structures with the NEC code are short, straight segments for modeling wires and flat patches for modeling surfaces. An antenna and any conducting objects in its vicinity that affect its performance must be modeled with strings of segments following the paths of wires and with patches covering surfaces.

Proper choice of the segments and patches for a model is the most critical step in obtaining accurate results.

1. Wire Modeling

A wire segment is defined by the coordinates of its two end points and its radius. Modeling a wire structure with segments involves both geometrical and electrical factors. Geometrically, the segments should follow the paths of conductors as closely as possible, using a piece-wise linear fit on curves. The following are the electrical considerations for wire segment modeling :

1. The segment length Δ relative to the wavelength λ :
   - Δ should be less than about 0.1 λ in order to get accurate results in most cases.
   - Somewhat longer segments may be acceptable on long wires with no abrupt changes while shorter segments, 0.05 λ or less may be needed in modeling critical regions of antenna.
   - Δ less than 0.001 λ should be avoided since similarity of the constant and cosine components of the current expansion can lead to numerical inaccuracy.
2. The wire radius, a, relative to λ is limited by the approximations used in the kernel of the electric field integratial equation. There are two approximation options, the thin-wire kernel and an extended thin-wire kernel. In the thin-wire kernel, currents on the surface are represented by a filament current on the segment axis. In the extended thin-wire kernel, a current uniformly distributed around the segment surface is assumed. The field of this current is approximated by the first two terms in a series expansion of the exact field in powers of a^2. Higher order approximations are not used. The first term in the series, which is independent of a, is identical to the thin-wire kernel while the second term extends the accuracy for larger values of a. Only currents in the axial direction on a segment are considered. The acceptability of these approximations depends on both the value of a/λ and the tendency of the excitation to produce circumferential current or current variation. Unless 2 $\pi a/\lambda$ is much less than 1, the validity of these approximations should be considered.
3. Connected segments must have identical coordinates for the connected ends. NEC assumes two end segments are connected if the separation between the end segment is less than 0.001 times the length of the shortest segment.
4. Segment intersection other than at ends does not allow current to flow from one segment to another.
5. Large radius changes in the wire should be avoided particularly if it consists of short segments. If the segment has large radius, then sharp bends should be avoided as well.
6. When modeling a solid structure with wire grid, a large number of segments should be used.
7. A segment is needed at the point where a network connection, a voltage, or a current source is located.
8. Base-fed wires connected to ground should be vertical.

9. The segments on either side of the citation source should be parallel and have the same length and radii.
10. Parallel wires should be several radii apart.
11. Before modeling a structure on the NPS main-frame, the limit of the number of segments and the number of connection points should be checked in the log of dimension changes by inspecting the code for the particular version of NEC from the Fortran library.

2. Modeling Stuctures Over Ground

Several options are available in NEC for modeling an antenna over a ground plane. For a perfectly conducting ground, the code generates an image of the structure reflected in the ground surface. The image is exactly equivalent to a perfectly conducting ground and results in solution accuracy comparable to that for a free space model. Structures may be close to the ground or contacting it in this case.

A finitely conducting ground may be modeled by an image modified by using the Sommerfeld method (available for wires only). The interpolation table must be generated by running a separate program SOMNTX using an input file of type SDATA containing ground parameters and frequency prior to the NEC run.

Both perfectly conducting and finitely conducting ground have the same height restriction for horizontal wires above the ground. For the horizontal wire with radius a, and height h, $(h^2 + a^2)^{1/2}$ should be greater than about 10^{-6} wavelengths. Futhermore, the height should be at least several times the radius for the thin-wire approximation to be valid.

APPENDIX B. INPUT DATA SETS USED FOR THE COMPUTER MODELS

1. The following data set was used to obtain antenna gain power patterns for the ARMY (lowband) DD antennas over perfect ground at 2 MHz. The antenna gain is calculated for each frequency from 2 to 8 MHz. The antenna gain radiation pattern over the real ground (fair ground) conditions was computed using the Sommerfeld method. The GN card for fair ground conditions is :

```
GN2, 0, 0, 0, 12, 0.005
```

```
CM       THE ARMY SIGNAL CORPS LO FREQ DOUBLE DELTA
CM
CM                 FROM TM 11-486-6
CM
CE
GW1, 45, 0, 0, 0, 150, 0, 0, .3            LONG HORIZ. WIRE
GW2, 50, 0, 0, 65, 150, 0, 0, .3           LONG SLANT WIRE
GW3, 20, 0, 0, 0, 0, 65, 0, .3             SHORT HORIZ. WIRE
GW4, 30, 0, 0, 65, 0, 65, 0, .3            SHORT SLANT WIRE
GM0, 0, 0, 0, 0, .7, .7, 3, 001.005
GR0, 2                                     ROTATE FOR 2 OTHER LEGS/SYMMETERY
GS1                                        SCALING
GE1                                        SYMMETRY FLAG/GND PLANE
GN1                                        PERFECT GROUND
FR0, 0, 0, 0, 2                            FREQUENCY 2 MHZ
WG                                         WRITE GREEN FUNCTION
NX                                         NEXT STRUCTURE
CE
GF                                         GREEN FUNCTION OPTION
GW66, 1, .7, .7, 3, -.7, -.7, 3, .3        LOAD WIRE
GW77, 1, .7, .7, 68, -.7, -.7, 68, .3      FEED WIRE
GS1                                        SCLALING
GE1                                        SYMETRIC FLAG/GND PLANE
LD0, 77, 1, 1, 600                         LOAD 600 OHM
EX0, 66, 1, 0, 1                           EXCITATION
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 0, 1, 0             PHI AT 0 VARY OF THETA
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 90, 1, 0            PHI AT 90 VARY OF THETA
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 70, 0, 0, 1              THETA AT 70 VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 50, 0, 0, 1              THETA AT 50 VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 30, 0, 0, 1              THETA AT 30 VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 10, 0, 0, 1              THETA AT 10 VARY OF PHI
```

```
XQ
EN
```

2. The following data set was used to obtain antenna gain power patterns for the ARMY (highband) DD Antenna over perfect ground at 8 MHZ. The antenna gain is calculated for each frequency from 8 to 30 MHz. Computation over fair ground conditions uses the GN card as described on the first data set.

```
CM     THE ARMY SIGNAL CORPS HI DOUBLE DELTA
CM               FROM TM 11-486-6
CE
GW1, 20, 0, 0, 0, 65, 0, 0, .3      HORIZONTAL WIRE
GW2, 30, 0, 0, 65, 65, 0, 0, .3     SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 3, 001.00    RAISE IT UP 3 FEET OFF THE GROUND
GR0, 4                              ROTATE FOR 3 OTHER LEGS/SYMMETERY
GS1                                 SCALING
GE1                                 SYMMETRY FLAG/GND PLANE
GN1                                 PERFECT GROUND
FR0, 0, 0, 0, 8                     FREQUENCY
EX0, 1, 1, 0, 1                     EXCITATION
EX0, 1, 21, 0, 1                    EXCITATION
EX0, 1, 41, 0, -1                   EXCITATION
EX0, 1, 61, 0, -1                   EXCITATION
LD0, 2, 1, 1, 600                   LOAD A SYMMETRIC SECTION 600 OHM
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 0, 1, 0      PHI AT 0 VARY OF THETA
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 90, 1, 0     PHI AT 90 VARY OF THETA
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 70, 0, 0, 1       THETA AT 70 VARY OF PHI
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 50, 0, 0, 1       THETA AT 50 VARY OF PHI
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 30, 0, 0, 1       THETA AT 30 VARY OF PHI
PL3, 1, 0, 4                        VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 10, 0, 0, 1       THETA AT 10 VARY OF PHI
XQ
EN
```

3. The following data set was used to obtain antenna gain power patterns for the USAF (lowband) DD Antenna over perfect ground at 2 MHz. The antenna gain is computed for each frequency from 2 to 8 MHz. Computation over fair ground conditions uses the GN card as described on the first data set.

```
CM   THE AIR FORCE LO FREQ DOUBLE DELTA ANTENNA
CM        FROM AFCS MEMO OF 08 APRIL 79
CE
GW1, 30, 0, 0, 0, 100, 0, 0, .01    HORIZ. WIRE
GW2, 35, 0, 0, 33, 100, 0, 0, .01   SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 5, 001.003   RAISE IT UP 5 FEET OFF THE GROUND
GM0, 0, 0, 0, 30, 0, 0, 0, 001.003  ROTATE FM XZ-PLANE TO POSITION
GX0, 110                            REFLECT IN X & Y FOR REST OF IT
```

```
GS1                                  SCALING
GE1                                  SYMMETRY FLAG/GND PLANE
GN1                                  PERFECT GROUND
FR0, 0, 0, 0, 2                      FREQUENCY
EX0, 1, 1, 0, 1                      EXCITATION
EX0, 1, 31, 0, -1                    EXCITATION
EX0, 1, 61, 0, 1                     EXCITATION
EX0, 1, 91, 0, -1                    EXCITATION
LD0, 2, 1, 1, 600                    LOAD A SYMM. SECTION 600 OHM
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 0, 1, 0       PHI AT 0 AND VARY OF THETA
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 90, 1, 0      PHI AT 90 AND VARY OF THETA
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 70, 0, 0, 1        THETA AT 70 AND VARY OF PHI
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 50, 0, 0, 1        THETA AT 50 AND VARY OF PHI
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 30, 0, 0, 1        THETA AT 30 AND VARY OF PHI
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 10, 0, 0, 1        THETA AT 10 AND VARY OF PHI
XQ
EN
```

4. The following data set was used to obtain antenna gain power patterns for the USAF (highband) DD Antenna over perfect ground at 8 MHz. The antenna gain is computed for each frequency from 8 to 30 MHz. Computation over fair ground conditions uses the GN card as described on the first data set.

```
CM    THE AIR FORCE HI FREQ DOUBLE DELTA ANTENNA
CM         FROM AFCS MEMO OF 08 APRIL 79
CE
GW1, 15, 0, 0, 0, 50, 0, 0, .01      HORIZ. WIRE
GW2, 18, 0, 0, 33, 50, 0, 0, .01     SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 5, 001.003    RAISE IT UP 5 FEET OFF THE GROUND
GM0, 0, 0, 0, 30, 0, 0, 0, 001.003   ROTATE FM XZ-PLANE TO POSITION
GX0, 110                             REFLECT IN X & Y FOR REST OF IT
GS1                                  SCALING
GE1                                  SYMMETRY FLAG/GND PLANE
GN1                                  PERFECT GROUND
FR0, 0, 0, 0, 8                      FREQUENCY
EX0, 1, 1, 0, 1                      EXCITATION
EX0, 1, 16, 0, -1                    EXCITATION
EX0, 1, 31, 0, 1                     EXCITATION
EX0, 1, 46, 0, -1                    EXCITATION
LD0, 2, 1, 1, 600                    LOAD A SYMM. SECTION 600 OHM
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 0, 1, 0       PHI AT 0 AND VARY OF THETA
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 90, 1, 0      PHI AT 90 AND VARY OF THETA
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 70, 0, 0, 1        THETA AT 0 AND VARY OF PHI
PL3, 1, 0, 4                         VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 50, 0, 0, 1        THETA AT 50 AND VARY OF PHI
```

```
PL3, 1, 0, 4                            VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 30, 0, 0, 1           THETA AT 30 AND VARY OF PHI
PL3, 1, 0, 4                            VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 10, 0, 0, 1           THETA AT 10 AND VARY OF PHI
XQ
EN
```

5. The following data set was used to obtain antenna gain power patterns for the ESI 32A2A DD Antenna over perfect ground at 2 MHz. The antenna gain is computed for each frequency from 2 to 30 MHz. Computation over fair ground conditions uses the GN card as described on the first data set.

```
CM          THE ESI 32A2A DOUBLE DELTA ANTENNA
CM                 8 - 32 MUZZ MODEL
CE
GW1, 25, 0, 0, 9.71, 74.695, 0, 1.65, .01  LOWER HORIZONTAL WIRE
GW2, 3, 74.695, 0, 1.65, 79.346, 0, 9, .01 OUTER VERTICAL SHUNT WIRE
GW3, 35, 0, 0, 76.54, 79.346, 0, 9, .01    SLANT WIRE
GM0, 0, 0, 0, 30, 0, 0, 0, 001.004         ROTATE FM XZ-PLANE TO POSITION
GM0, 1, 0, 0, -60, 0, 0, 0, 001.004        CREATE SECOND LEG OF FRONT HALF
GR10, 2                                    CREATE THE BACK HALF
GS1                                        SCALING
GE1                                        SET SYMM/GND FLAG
GN1                                        PERFECT GROUND
FR0, 0, 0, 0, 2                            FREQUENCY
EX0, 1, 1, 0, 1                            EXCITATION
EX0, 1, 26, 0, -1                          EXCITATION
EX0, 11, 1, 0, -1                          EXCITATION
EX0, 11, 26, 0, 1                          EXCITATION
LD0, 3, 1, 1, 600                          LOAD THE TOP SEGMENTS 600 OHM
LD0, 3, 36, 36, 600
LD0, 13, 1, 1, 600
LD0, 13, 36, 36, 600
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 0, 1, 0             PHI AT 0 AND VARY OF THETA
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 91, 1, 1500, -90, 90, 1, 0            PHI AT 90 AND VARY OF THETA
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 70, 0, 0, 1              THETA AT 70 AND VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 50, 0, 0, 1              THETA AT 50 AND VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 30, 0, 0, 1              THETA AT 30 AND VARY OF PHI
PL3, 1, 0, 4                               VERT, HORZ AND TOTAL GAIN
RP0, 1, 91, 1500, 10, 0, 0, 1              THETA AT 10 AND VARY OF PHI
XQ
EN
```

6. The following data set was used to calculate impedance and VSWR for the ARMY (highband) DD antenna from 8 - 30 MHz over perfect ground using a normalized impedance of 50 ohms. To calculate input impedance using 300 and 600 ohms, change the value of normalized impedance in the EX card accordingly.

```
CM        THE ARMY SIGNAL CORPS HI FREQ DOUBLE DELTA
CM                  FROM TM 11-486-6
CE
GW1, 20, 0, 0, 0, 65, 0, 0, .3     HORIZONTAL WIRE
GW2, 30, 0, 0, 65, 65, 0, 0, .3    SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 3, 001.003  RAISE IT UP 3 FEET OFF THE GROUND
GR0, 4                             ROTATE FOR 3 OTHER LEGS/SYMMETERY
GS1                                SCALING
GE1                                SYMMETRY FLAG/GND PLANE
GN1                                PERFECT GROUND
FR0, 23, 0, 0, 8, 1                FREQUENCY 8 TO 30 MHZ
LD0, 2, 1, 1, 600                  LOAD A SYMMETRIC SECTION 600 OHM
EX0, 1, 1, 01, 1, 0, 50            EXCITATIONS,
EX0, 1, 21, 01, 1, 0, 50           NORMALIZED IMPEDANCE 50 OHM
EX0, 1, 41, 01, -1, 0, 50
EX0, 1, 61, 01, -1, 0, 50
PL4                                IMPEDANCE, VSWR
XQ
EN
```

7. The following data set was used to calculate impedance and VSWR for the USAF (lowband) DD antenna from 2 - 8 MHz over perfect ground using a normalized impedance of 50 ohms.

```
CM        THE AIR FORCE LO FREQ DOUBLE DELTA
CM           FROM AFCS MEMO OF 08 APR 79
CE
GW1, 30, 0, 0, 0, 100, 0, 0, .01     HORIZ. WIRE
GW2, 35, 0, 0, 33, 100, 0, 0, .01    SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 5, 001.003    RAISE IT UP 5 FEET OFF THE GROUND
GM0, 0, 0, 0, 30, 0, 0, 0, 001.003   ROTATE FM XZ-PLANE TO POSITION
GX0, 110                             REFLECT IN X & Y FOR REST OF IT
GS1                                  SCALING
GE1                                  SYMMETRY FLAG/GND PLANE
GN1                                  PERFECT GROUND
FR0, 7, 0, 0, 2, 1                   FREQUENCY 2 TO 8 MHZ
LD0, 2, 1, 1, 600                    LOAD A SYMM. SECTION 600 OHM
EX0, 1, 1, 01, 1, 0, 50              EXCITATIONS,
EX0, 1, 31, 01, -1, 0, 50            NORMALIZED IMPEDANCE 50 OHM
EX0, 1, 61, 01, 1, 0, 50
EX0, 1, 91, 01, -1, 0, 50
PL4                                  IMPEDANCE, VSWR
XQ
EN
```

8. The following data set was used to calculate impedance and VSWR for the USAF (highband) DD antenna from 8 - 30 MHz over perfect ground using a normalized impedance of 50 ohms.

```
CM        THE AIR FORCE HI FREQ DOUBLE DELTA
CM           FROM AFCS MEMO OF 08 APR 79
CE
GW1, 15, 0, 0, 0, 50, 0, 0, .01     HORIZ. WIRE
```

```
GW2, 18, 0, 0, 33, 50, 0, 0, .01       SLANT WIRE
GM0, 0, 0, 0, 0, 0, 0, 5, 001.003      RAISE IT UP 5 FEET OFF THE GROUND
GM0, 0, 0, 0, 30, 0, 0, 0, 001.003     ROTATE FM XZ-PLANE TO POSITION
GX0, 110                               REFLECT IN X & Y FOR REST OF IT
GS1                                    SCALING
GE1                                    SYMMETRY FLAG/GND PLANE
GN1                                    PERFECT GROUND
FR0, 23, 0, 0, 8, 1                    FREQUENCY 8 TO 30 MHZ
LD0, 2, 1, 1, 600                      LOAD A SYMM. SECTION 600 OHM
EX0, 1, 1, 01, 1, 0, 50                EXCITATIONS,
EX0, 1, 16, 01, -1, 0, 50              NORMALIZED IMPEDANCE 50 OHM
EX0, 1, 31, 01, 1, 0, 50
EX0, 1, 46, 01, -1, 0, 50
PL4                                    IMPEDANCE, VSWR
XQ
EN
```

9. The following data set was used to calculate impedance and VSWR for the ESI 32A2A DD atenna from 2 - 30 MHz over perfect ground using a normalized impedance of 50 ohms.

```
CM       THE ESI 32A2A DOUBLE DELTA ANTENNA
CM            8 - 32 MUZZ MODEL
CE
GW1, 25, 0, 0, 9.71, 74.695, 0, 1.65, .01  LOWER HORIZONTAL WIRE
GW2, 3, 74.695, 0, 1.65, 79.346, 0, 9, .01 OUTER VERTICAL SHUNT WIRE
GW3, 35, 0, 0, 76.54, 79.346, 0, 9, .01    SLANT WIRE
GM0, 0, 0, 0, 30, 0, 0, 0, 001.004         ROTATE FM XZ-PLANE TO POSITION
GM0, 1, 0, 0, -60, 0, 0, 0, 001.004       CREATE SECOND LEG OF FRONT HALF
GR10, 2                                    CREATE THE BACK HALF
GS1                                        SCALING
GE1                                        SET SYMM/GND FLAG
GN1                                        PERFECT GROUND
FR0, 29, 0, 0, 2, 1                        FREQUENCY 2 TO 30 MHZ
EX0, 1, 1, 01, 1, 0, 50                    EXCITATIONS,
EX0, 1, 26, 01, -1, 0, 50                  NORMALIZED IMPEDANCE 50 OHM
EX0, 11, 1, 01, -1, 0, 50
EX0, 11, 26, 01, 1, 0, 50
LD0, 3, 1, 1, 600                          LOAD THE TOP SEGMENTS 600 OHM
LD0, 3, 36, 36, 600
LD0, 13, 1, 1, 600
LD0, 13, 36, 36, 600
PL4                                        IMPEDANCE, VSWR
XQ
EN
```

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